

Kent Academic Repository

Full text document (pdf)

Citation for published version

Angius, Luca and Hopker, James G. and Mauger, Alexis R. (2017) The ergogenic effects of transcranial direct current stimulation on exercise performance. *Frontiers in Physiology*, 8 (90). pp. 1-7. ISSN 1664-042X.

DOI

<https://doi.org/10.3389/fphys.2017.00090>

Link to record in KAR

<http://kar.kent.ac.uk/60189/>

Document Version

Author's Accepted Manuscript

Copyright & reuse

Content in the Kent Academic Repository is made available for research purposes. Unless otherwise stated all content is protected by copyright and in the absence of an open licence (eg Creative Commons), permissions for further reuse of content should be sought from the publisher, author or other copyright holder.

Versions of research

The version in the Kent Academic Repository may differ from the final published version.

Users are advised to check <http://kar.kent.ac.uk> for the status of the paper. **Users should always cite the published version of record.**

Enquiries

For any further enquiries regarding the licence status of this document, please contact:

researchsupport@kent.ac.uk

If you believe this document infringes copyright then please contact the KAR admin team with the take-down information provided at <http://kar.kent.ac.uk/contact.html>

The ergogenic effects of transcranial direct current stimulation on exercise performance

Luca Angius¹, James Hopker¹, Alexis R. Mauger^{1*}

¹School of Sport & Exercise Sciences, University of Kent, United Kingdom

Submitted to Journal:

Frontiers in Physiology

Specialty Section:

Exercise Physiology

ISSN:

1664-042X

Article type:

Mini Review Article

Received on:

29 Sep 2016

Accepted on:

01 Feb 2017

Provisional PDF published on:

01 Feb 2017

Frontiers website link:

www.frontiersin.org

Citation:

Angius L, Hopker J and Mauger AR(2017) The ergogenic effects of transcranial direct current stimulation on exercise performance. *Front. Physiol.* 8:90. doi:10.3389/fphys.2017.00090

Copyright statement:

© 2017 Angius, Hopker and Mauger. This is an open-access article distributed under the terms of the [Creative Commons Attribution License \(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use, distribution and reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

This Provisional PDF corresponds to the article as it appeared upon acceptance, after peer-review. Fully formatted PDF and full text (HTML) versions will be made available soon.

1 **The ergogenic effects of transcranial direct current stimulation on exercise**
2 **performance**

3 Angius L.¹, Hopker J.¹, Mauger A.R.¹

4
5 ¹ Endurance Research Group, School of Sport and Exercise Sciences, University of Kent,
6 Chatham Maritime, (UK).

7
8 **Affiliation:** Endurance Research Group, School of Sport and Exercise Sciences, University of
9 Kent, Chatham Maritime, (UK).

10
11 **Corresponding author:**

12 Dr Lex Mauger

13 School of Sport and Exercise Sciences

14 University of Kent

15 Chatham Maritime

16 Kent, ME4 4AG.

17 Tel: +44 (0)1634 888997.

18 Fax: +44 (0)1634 888890.

19 Email: L.Mauger@kent.ac.uk

Abstract

20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48

The physical limits of the human performance have been the object of study for a considerable time. Most of the research has focused on the locomotor muscles, lungs and heart. As a consequence, much of the contemporary literature has ignored the importance of the brain in the regulation of exercise performance. With the introduction and development of new non-invasive devices, the knowledge regarding the behaviour of the central nervous system during exercise has advanced. A first step has been provided from studies involving neuroimaging techniques where the role of specific brain areas have been identified during isolated muscle or whole-body exercise. Furthermore, a new interesting approach has been provided by studies involving non-invasive techniques to manipulate specific brain areas. These techniques most commonly involve the use of an electrical or magnetic field crossing the brain. In this regard, there has been emerging literature demonstrating the possibility to influence exercise outcomes in healthy people following stimulation of specific brain areas. Specifically, transcranial direct current stimulation (tDCS) has been recently used prior to exercise in order to improve exercise performance under a wide range of exercise types. In this review article, we discuss the evidence provided from experimental studies involving tDCS. The aim of this review is to provide a critical analysis of the experimental studies investigating the application of tDCS prior to exercise and how it influences brain function and performance. Finally, we provide a critical opinion of the usage of tDCS for exercise enhancement. This will consequently progress the current knowledge base regarding the effect of tDCS on exercise and provides both a methodological and theoretical foundation on which future research can be based.

49

Introduction

50 During sustained submaximal contraction, the excitability of spinal motoneurons and
51 the contractile capacity of the muscle fibers are reduced (Allen et al., 2008; Butler et al., 2003),
52 so that in order to maintain the required force or power, the input to the spinal motoneurons
53 must increase (Taylor et al., 1996). This input (also called descending drive) is likely to
54 originate from the corticospinal pathway, and previous experiments have demonstrated a
55 number of factors which may moderate this (Enoka et al., 2011; Gandevia, 2001). In this
56 regard, a failure to generate output from the motor cortex (M1) has been defined as supraspinal
57 fatigue, and together with peripheral mechanisms, participates in muscle fatigue (Gandevia,
58 2001). Previous studies have suggested that the development supraspinal fatigue is
59 accompanied by changes in motor cortex excitability (Taylor et al., 1996).

60 Interventions that increase M1 excitability might increase the output from M1 (increase
61 descending drive) thus delaying the development of supraspinal fatigue and therefore
62 improving exercise capacity (Cogiamanian et al., 2007; Williams et al., 2013). In this regard,
63 a neuromodulatory technique called transcranial direct current stimulation (tDCS) has been
64 widely used to modulate the excitability of a targeted brain area through the application of a
65 weak electrical current across the scalp. The electrical current alters the resting membrane
66 potential of the targeted neurons, with the anodal electrode being excitatory and the cathodal
67 being inhibitory (George & Aston-Jones, 2010; Nitsche et al., 2008). These effects can persist
68 for up to 90 min following 9-13 min of stimulation (Nitsche & Paulus, 2001). Studies have
69 demonstrated that acute tDCS is a safe neuromodulatory brain technique, with no or only minor
70 side effects (Frank et al., 2010; Fregni et al., 2006; Palm et al., 2008; Poreisz et al., 2007) and
71 is both cheap and easy to administer. Therefore, interest in tDCS' ergogenic potential has
72 grown considerably.

73 Research has only recently started to investigate the effect of tDCS on physical
74 performance and, given the prominent role of the motor and premotor brain regions in the
75 development of supraspinal fatigue (Gandevia, 2001), most of studies have attempted to target
76 these areas. To date, there are a limited number of studies, showing inconsistent results and
77 often with flawed methodological design. Nevertheless, the balance of evidence suggests that
78 tDCS might have a positive effect on exercise capacity. A summary of the most significant
79 studies on tDCS stimulation and exercise performance are shown in Table 1. For the purpose
80 of this review we considered studies that adhered to the following criteria:

81

- 82 - Acute administration of tDCS prior to, or during, exercise in healthy participants;
- 83 - Continuous exercise lasting at least 75 s (Gastin, 2001);
- 84 - Exercise tasks involving time to exhaustion, time trial or incremental exercise testing.

85

86 Selected studies were divided into either single joint isometric or whole body exercise.
87 While whole-body exercise better represents real sporting competition, single-joint exercises
88 potentially permit a better and more controlled exploration of the physiological mechanisms
89 associated with fatigue. This distinction is fundamental as the two exercise modalities differ in
90 terms of metabolic, cardiorespiratory, and psychological demand, and therefore differently
91 affect brain activity (Sidhu et al., 2013). Studies were then ordered according to publication
92 date.

93 The aim of this mini-review is to provide a framework to discuss and analyse the studies
94 involving acute administration of tDCS with the aim of improving exercise performance. A
95 brief analysis of the physiological and psychological mechanisms and methodological
96 limitations has been provided in order to improve the understanding of the effect of tDCS on
97 exercise performance.

98

99 Studies on single joint isometric exercise

100 The first study investigating the effect of tDCS on exercise performance was performed
101 by Cogiamanian and colleagues (2007), and was comprised of two experiments. In the first,
102 participants were divided in two groups (brain polarization and control) with both completing
103 two elbow flexor isometric time to exhaustion (TTE) tasks. Prior to the second task, the brain
104 polarized group received anodal or cathodal tDCS while the control group did not receive any
105 tDCS administration. The second experiment aimed to monitor the corticospinal response
106 following tDCS administration. No changes in MVC or EMG activity were found, but the
107 second TTE was significantly longer following anodal tDCS, with a significant increase in
108 corticospinal excitability observed in the second experiment. The authors were not able to
109 provide a precise explanation for the improvement in TTE, but suggested that tDCS could act
110 upstream of the M1 by facilitating the supraspinal drive or by protecting the M1 from inhibitory
111 feedback arising from working muscles.

112 Two different studies partially replicated the study of Cogiamanian and colleagues
113 (2007). Kan et al. (2013) performed a crossover study where participants performed a protocol
114 similar to that used by Cogiamanian et al., (2007), but with a lower contraction intensity (30%
115 MVC) and different tDCS montage (see Table 1). No changes in MVC, torque fluctuation,

116 EMG and perceived pain were found, with no improvement in TTE duration. The study of
117 Muthalib et al., (2013) mainly aimed to monitor level of prefrontal oxygenation, and similarly
118 to Kan et al (2013), there was no improvement in MVC or TTE duration, along with no changes
119 in prefrontal oxygenation following tDCS. However, Muthalib et al., (2013) monitored
120 oxygenation in an area distant to the tDCS electrode location (M1), which might explain the
121 lack of change in prefrontal oxygenation. Unfortunately, none of the above studies monitored
122 the corticospinal response and therefore it is not possible to establish whether tDCS was able
123 to increase corticospinal excitability.

124 A further experiment investigating the effect of tDCS on sustained isometric
125 contraction was performed by Williams et al., (2013). In a crossover study, participants were
126 asked to perform an isometric TTE at 20% MVC of the elbow flexors. Initially, no
127 improvement in performance after anodal tDCS (compared to sham) was observed.
128 Subsequently, the investigators divided participants in two sub groups: one group where TTE
129 time was shorter than tDCS administration time (n=8), and one group where TTE time was
130 longer than tDCS administration time (n=10). The first group showed a significant
131 improvement in performance compared to the second. No significant changes in motor-evoked
132 potentials (MEP) were found between conditions or group, but ratings of perceived exertion
133 (RPE) were significantly reduced in the anodal tDCS condition. The subdivision of the
134 participants according to task duration raises some doubts regarding the true efficacy of tDCS,
135 and the experimental findings question whether tDCS is beneficial only when stimulation
136 occurs during exercise and only to those with lower endurance capacity.

137 With the aim to provide a better understanding of tDCS mechanisms, Abdelmoula et
138 al. (2016), monitored several muscles in a similar protocol to Cogiamanian et al., (2007).
139 Similar to the findings of Cogiamanian et al., (2007), TTE duration was longer following
140 anodal tDCS. However, this occurred in the absence of any change in neuromuscular,
141 corticospinal or perceptual parameters. In fact, MVC, coefficient of variation of torque, EMG
142 activity during exercise, MEP responses and RPE did not differ between conditions. Because
143 of the increase in TTE duration in the absence of changes in neuromuscular or corticospinal
144 response, the authors proposed that the large tDCS electrode might have facilitated adjacent
145 brain areas which affected the sensorimotor integration and the associated cognitive demand
146 during the task without producing any change in the central motor command. This study
147 however did not provide any evidence to support this suggestion.

148 The benefits of tDCS have been extended to older populations (Oki et al., 2016), with
149 older adults being shown to have lower cortical excitability following tDCS than younger

150 adults (Oliviero et al., 2006). Together with an increase in TTE duration after anodal tDCS, a
151 slower increase in RPE was observed in agreement with previous experiments (Angius et al.,
152 2016; Okano et al., 2015; Williams et al., 2013). The authors (Oki et al., 2016) suggested that
153 the increased excitability of the M1 could have reduced the neural drive necessary to perform
154 the task, which therefore lowered RPE. An association between the magnitude of the effect of
155 tDCS and baseline level of muscle strength was found ($r = -.55$; $p = .05$). This may suggest that
156 weaker subjects could receive more benefits compared to stronger subjects, although the
157 authors did not further investigate this potential. Only 45% of the subjects demonstrated a
158 positive response to tDCS, and so these findings might also in part explain the different
159 outcomes across tDCS studies, as the efficacy of tDCS might rely on high responder
160 participants. Future studies should therefore take into account such variables when determining
161 the participant cohort.

162 Angius et al. (2016) compared the effect of two tDCS montages (see Table 1) on TTE
163 of knee extensors. TTE was significantly longer when an extracephalic montage was used
164 without any effect on corticospinal and peripheral parameters. A reduction in RPE was found
165 when the extracephalic montage was used, while HR and pain were unchanged. As no effect
166 on corticospinal and peripheral parameters was found, the exact mechanisms explaining the
167 improvement in TTE are still uncertain. However, the absence of effect on the corticospinal
168 response could be due to the contraction intensity used (50% MVC) for the neuromuscular
169 assessment. Indeed, the largest MEP response has been shown to occur at 50% MVC (Goodall
170 et al., 2014), which could have masked the tDCS effect on this variable. This study suggests
171 that an extracephalic montage is more appropriate for the improvement in exercise capacity,
172 and could explain the null effect of tDCS shown in previous studies involving whole body
173 exercise (Angius et al., 2015; Barwood et al., 2016).

174

175 Studies on whole body dynamic exercise

176 The first study investigating the effect of tDCS on whole body exercise was conducted
177 by Okano et al., (2015). In a crossover, randomized experimental design, participants
178 performed maximal cycling exercise up to volitional exhaustion. Following anodal tDCS,
179 maximal power output improved by ~4%, and RPE and HR were lower compared to a sham
180 condition (although they were not affected in the latter stages of the test). The authors suggested
181 that anodal stimulation could have affected the activity of the insular cortex, thus reducing RPE
182 and leading to an improvement in performance.

183 Angius et al., (2015) investigated the effect of tDCS on exercise-induced muscle pain
184 during cycling TTE and on pain perception during a cold pressor test. The authors did not find
185 changes in TTE duration and physiological or perceptual parameters during exercise. However,
186 following tDCS a significant reduction in perceived pain during the cold pressor test was found.
187 The lack of effect during cycling was likely caused by the different type of pain stimulus, pain
188 intensity perceived, or the attentional focus during each task. Furthermore, the authors
189 suggested that the lack of effect on exercise performance could have been due to the tDCS
190 montage used (Table 1), as any benefits from the anodal electrode on the M1 could have been
191 negated by the cathodal electrode over the dorsolateral prefrontal cortex. The authors therefore
192 suggested that a bilateral extracephalic tDCS montage would be more appropriate for whole
193 body exercise.

194 An improvement in cycling TTE following tDCS was demonstrated by Costa et al.,
195 (2015). Despite the effect on TTE, no changes in mood, physiological or perceptual parameters
196 were reported. It should be noted that a trend for a lower RPE following anodal tDCS was
197 found ($p = 0.07$), suggesting that the increased M1 excitability could have made exercise feel
198 easier for a given intensity (Abdelmoula et al., 2016; Angius et al., 2016; Williams et al., 2013).
199 The authors suggested that the improvement in TTE was the consequence of an increase in
200 intracortical facilitation and M1 excitability, although this hypothesis could not be confirmed
201 as the necessary corticospinal parameters were not monitored. In addition, the tDCS montage
202 in this study placed one electrode over the occipital protuberance, and as a consequence the
203 direction of current between the two electrodes could have interfered with other brain areas,
204 thus affecting both physiological and perceptual parameters.

205 Angius and colleagues (2016) showed an ergogenic effect of tDCS in whole-body
206 exercise, with TTE duration increasing following anodal tDCS, paralleled a lower RPE. There
207 were no differences observed in the cathodal and sham tDCS conditions. Following anodal
208 tDCS, an increase in corticospinal excitability of the knee extensor muscles was also reported,
209 leading the authors to suggest that the increased excitability of the M1 could have augmented
210 the output to the working muscles by consequently reducing the central command required.
211 This could have caused the lower RPE, leading participants to perceive the exercise as easier.
212 However, no further evidence to support this hypothesis was provided, and so speculation on
213 such a mechanism should be treated with caution.

214 In two two separate studies, Barwood et al., (2016) investigated the effects of tDCS on
215 a 20 km cycling time trial and a TTE test in hot conditions. The same montage used by Okano
216 and colleagues (2015) was applied with the hypothesis that tDCS would reduce the RPE for a

217 given intensity and therefore improve cycling performance. No changes in performance in
218 either exercise protocols were found, with no differences in RPE. Unlike Okano et al., (2015)
219 no reduction in HR following tDCS was reported. As proposed by the authors, the discrepancy
220 in exercise outcome compared to Okano et al., (2015) might have been caused by a non-
221 appropriate blinding procedure, and the lack of effect in HR may have been due to the high
222 work rate adopted. The null effects may also have been due to the negative effect of the cathodal
223 electrode. Furthermore, hyperthermia has been well demonstrated to induce changes in
224 metabolic and cardiovascular demand together with an increase in central fatigue (Nybo &
225 Nielsen, 2001), which may negate any benefits of anodal stimulation.

226

227 Possible mechanisms of actions and limitations

228 Collectively, experiments to date provide interesting insights regarding the possible
229 ergogenic effects of tDCS on exercise in healthy individuals. Despite the differences across
230 each study regarding the experimental design, task performed and tDCS montage, there are
231 some experimental findings which are similar across the various experiments. Firstly, acute
232 tDCS over the M1 does not seem to improve maximal isometric force capacity (Angius et al.,
233 2015, 2016a, 2016b; Cogiamanian et al., 2007; Kan et al., 2013; Williams et al., 2013).
234 Secondly, tasks performed at a submaximal intensity are generally improved by tDCS
235 (Abdelmoula et al., 2016; Angius et al., 2015, 2016a, 2016b; Cogiamanian et al., 2007;
236 Williams et al., 2013). Thirdly, none of the physiological or neuromuscular parameters (aside
237 from corticospinal excitability) during exercise seem to be affected by tDCS.

238 Regarding the inconsistency across each study, previous research has demonstrated a
239 range of responses following tDCS stimulation from little or no effect, to a large effect with
240 high variability in corticospinal excitability (Horvath et al., 2015, 2016; Madhavan et al.,
241 2016). Moreover, there is an absence of a standardised and reliable protocol to monitor the
242 effect of tDCS on the neuromuscular response (Madhavan et al., 2016). Therefore, it is not
243 surprising that improvements in performance were accompanied with no changes in
244 neuromuscular function with particular interest on the corticospinal pathway. Finally, the
245 absence of rigorous blinding procedures in a considerable number of studies (see Table 1)
246 might contribute to the mixed results currently seen in the literature, and so where this is
247 apparent the results must be interpreted with caution.

248 The exact mechanisms by which tDCS improves exercise performance are still
249 unknown. It is suggested that tDCS likely facilitates the M1 by increasing its output during
250 exercise and possibly reducing supraspinal fatigue (Cogiamanian et al., 2007; Williams et al.,

251 2013). However, this hypothesis is in contrast with previous studies as the improvement in
252 performance appears not to rely on changes in corticospinal response (Abdelmoula et al.,
253 2016). Other authors suggest that the lower RPE following tDCS administration might explain
254 the improvement in performance (Okano et al., 2015b; Angius et al., 2016a, 2016b). Changes
255 in RPE have been related to the magnitude of central motor command originating from activity
256 of motor/premotor brain areas (de Morree et al., 2012, 2014). Thus, if M1 excitability is
257 increased following tDCS administration, it needs to receive less input to generate the amount
258 of output required to recruit the muscle, hence, a lower RPE for a given force or power should
259 be expected. This hypothesis is supported by previous experiments involving non-invasive
260 brain stimulation where manipulation of premotor and motor brain areas induced variations in
261 RPE (Goodall et al., 2013; Takarada et al., 2014; Zénon et al., 2015). However, because of the
262 electrode size, the effects of the tDCS could possibly influence adjacent areas by influencing
263 the sensorimotor integration during muscular contraction without affecting the motor command
264 (Abdelmoula et al., 2016). To the best of our knowledge no studies have monitored the activity
265 of brain areas during exercise following tDCS stimulation and therefore development of a
266 mechanistic understanding is a clear priority.

267

268 Conclusion and perspectives

269 The promising outcomes of tDCS on exercise performance have recently attracted
270 attention for its potential to be used domestically for ergogenic purposes. Unlike TMS
271 equipment, tDCS devices are relatively small and easy to use and therefore its use by people
272 unaware of its potential effects has been reported (Reardon, 2016). Given the uncertain
273 mechanisms and the inconsistency of outcomes of tDCS prior to exercise, the use of tDCS prior
274 to/during exercise should be treated with some caution. Future research should seek to identify
275 the mechanisms underpinning the apparent ergogenic effect of tDCS, and focus should also be
276 given the effects of long-term use. As tDCS is clearly of interest not only to the scientific, but
277 also the public and commercial communities, researchers and publishers have a responsibility
278 to disseminate transparent and objective studies that can further our understanding of tDCS.

279 Currently, the different outcomes observed in tDCS research are likely a consequence
280 of differences between exercise type and/or tDCS set up (Table 1), and many of the
281 aforementioned studies were not designed to specifically assess the mechanism by which
282 performance was hypothesised to improve. Therefore, more studies which systematically
283 control the tDCS variables (e.g. montage, duration, location etc.) and allow assessment of the
284 mechanisms are required.

- 286 Abdelmoula A, Baudry S & Duchateau J (2016). Anodal transcranial direct current
287 stimulation enhances time to task failure of a submaximal contraction of elbow
288 flexors without changing corticospinal excitability. *Neuroscience* **322**, 94–103.
- 289 Allen DG, Lamb GD & Westerblad H (2008). Skeletal muscle fatigue: cellular mechanisms.
290 *Physiol Rev* **88**, 287–332.
- 291 Angius L, Hopker JG, Marcora SM & Mauger AR (2015a). The effect of transcranial direct
292 current stimulation of the motor cortex on exercise-induced pain. *Eur J Appl Physiol*
293 **115**, 2311–2319.
- 294 Angius L, Marcora S, Hopker J & Mauger L (2016a). Transcranial direct current stimulation
295 improves cycling performance in healthy individuals. *Proc Physiol Soc*. Available at:
296 <http://www.physoc.org/proceedings/abstract/Proc%20Physiol%20Soc%2035C03>
297 [Accessed June 18, 2016].
- 298 Angius L, Pageaux B, Hopker J, Marcora S & Mauger A (2015b). Transcranial direct current
299 stimulation improves isometric time to exhaustion performance of lower limbs. *Proc*
300 *Physiol Soc*. Available at:
301 <http://www.physoc.org/proceedings/abstract/Proc%20Physiol%20Soc%2034C54>
302 [Accessed November 16, 2015].
- 303 Angius L, Pageaux B, Hopker J, Marcora SM & Mauger AR (2016b). Transcranial direct
304 current stimulation improves isometric time to exhaustion of the knee extensors.
305 *Neuroscience*; DOI: 10.1016/j.neuroscience.2016.10.028.
- 306 Barwood MJ, Butterworth J, Goodall S, House JR, Laws R, Nowicky A & Corbett J (2016a).
307 The Effects of Direct Current Stimulation on Exercise Performance, Pacing and
308 Perception in Temperate and Hot Environments. *Brain Stimulat*; DOI:
309 10.1016/j.brs.2016.07.006.
- 310 Barwood MJ, Butterworth J, Goodall S, House JR, Laws R, Nowicky A & Corbett J (2016b).
311 The Effects of Direct Current Stimulation on Exercise Performance, Pacing and
312 Perception in Temperate and Hot Environments. *Brain Stimul Basic Transl Clin Res*
313 *Neuromodulation*; DOI: 10.1016/j.brs.2016.07.006.
- 314 Butler JE, Taylor JL & Gandevia SC (2003). Responses of human motoneurons to
315 corticospinal stimulation during maximal voluntary contractions and ischemia. *J*
316 *Neurosci* **23**, 10224–10230.
- 317 Cogiamanian F, Marceglia S, Ardolino G, Barbieri S & Priori A (2007a). Improved isometric
318 force endurance after transcranial direct current stimulation over the human motor
319 cortical areas. *Eur J Neurosci* **26**, 242–249.
- 320 Cogiamanian F, Marceglia S, Ardolino G, Barbieri S & Priori A (2007b). Improved isometric
321 force endurance after transcranial direct current stimulation over the human motor
322 cortical areas. *Eur J Neurosci* **26**, 242–249.

- 323 Enoka RM, Baudry S, Rudroff T, Farina D, Klass M & Duchateau J (2011). Unraveling the
324 neurophysiology of muscle fatigue. *J Electromyogr Kinesiol Off J Int Soc*
325 *Electrophysiol Kinesiol* **21**, 208–219.
- 326 Frank E, Wilfurth S, Landgrebe M, Eichhammer P, Hajak G & Langguth B (2010). Anodal
327 skin lesions after treatment with transcranial direct current stimulation. *Brain Stimulat*
328 **3**, 58–59.
- 329 Fregni F, Boggio PS, Nitsche MA, Rigonatti SP & Pascual-Leone A (2006). Cognitive
330 effects of repeated sessions of transcranial direct current stimulation in patients with
331 depression. *Depress Anxiety* **23**, 482–484.
- 332 Gandevia SC (2001a). Spinal and supraspinal factors in human muscle fatigue. **81**, 1725–
333 1789.
- 334 Gandevia SC (2001b). Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*
335 **81**, 1725–1789.
- 336 Gastin PB (2001). Energy system interaction and relative contribution during maximal
337 exercise. *Sports Med Auckl NZ* **31**, 725–741.
- 338 George MS & Aston-Jones G (2010). Noninvasive techniques for probing neurocircuitry and
339 treating illness: vagus nerve stimulation (VNS), transcranial magnetic stimulation
340 (TMS) and transcranial direct current stimulation (tDCS). *Neuropsychopharmacol Off*
341 *Publ Am Coll Neuropsychopharmacol* **35**, 301–316.
- 342 Goodall S, Howatson G, Romer L & Ross E (2014). Transcranial magnetic stimulation in
343 sport science: a commentary. *Eur J Sport Sci* **14 Suppl 1**, S332-340.
- 344 Goodall S, St Clair Gibson A, Voller B, Lomarev M, Howatson G, Dang N, Hortobágyi T &
345 Hallett M (2013). Repetitive Transcranial Magnetic Stimulation Attenuates the
346 Perception of Force Output Production in Non-Exercised Hand Muscles after
347 Unilateral Exercise. *PLoS ONE*; DOI: 10.1371/journal.pone.0080202.
- 348 Horvath JC, Forte JD & Carter O (2015). Evidence that transcranial direct current stimulation
349 (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude
350 modulation in healthy human subjects: A systematic review. *Neuropsychologia* **66**,
351 213–236.
- 352 Horvath JC, Vogrin SJ, Carter O, Cook MJ & Forte JD (2016). Effects of a common
353 transcranial direct current stimulation (tDCS) protocol on motor evoked potentials
354 found to be highly variable within individuals over 9 testing sessions. *Exp Brain Res*
355 **234**, 2629–2642.
- 356 Kan B, Dundas JE & Nosaka K (2013). Effect of transcranial direct current stimulation on
357 elbow flexor maximal voluntary isometric strength and endurance. *Appl Physiol Nutr*
358 *Metab Physiol Appliquée Nutr Métabolisme* **38**, 734–739.
- 359 Madhavan S, Sriraman A & Freels S (2016). Reliability and Variability of tDCS Induced
360 Changes in the Lower Limb Motor Cortex. *Brain Sci*; DOI: 10.3390/brainsci6030026.

- 361 de Morree HM, Klein C & Marcora SM (2012). Perception of effort reflects central motor
362 command during movement execution. *Psychophysiology* **49**, 1242–1253.
- 363 de Morree HM, Klein C & Marcora SM (2014). Cortical substrates of the effects of caffeine
364 and time-on-task on perception of effort. *J Appl Physiol Bethesda Md* 1985 **117**,
365 1514–1523.
- 366 Muthalib M, Kan B, Nosaka K & Perrey S (2013). Effects of transcranial direct current
367 stimulation of the motor cortex on prefrontal cortex activation during a neuromuscular
368 fatigue task: an fNIRS study. *Adv Exp Med Biol* **789**, 73–79.
- 369 Nitsche MA, Cohen LG, Wassermann EM, Priori A, Lang N, Antal A, Paulus W, Hummel F,
370 Boggio PS, Fregni F & Pascual-Leone A (2008). Transcranial direct current
371 stimulation: State of the art 2008. *Brain Stimulat* **1**, 206–223.
- 372 Nitsche MA & Paulus W (2001). Sustained excitability elevations induced by transcranial
373 DC motor cortex stimulation in humans. *Neurology* **57**, 1899–1901.
- 374 Nybo L & Nielsen B (2001). Hyperthermia and central fatigue during prolonged exercise in
375 humans. *J Appl Physiol Bethesda Md* 1985 **91**, 1055–1060.
- 376 Okano AH, Fontes EB, Montenegro RA, Farinatti P de TV, Cyrino ES, Li LM, Bikson M &
377 Noakes TD (2015a). Brain stimulation modulates the autonomic nervous system,
378 rating of perceived exertion and performance during maximal exercise. *Br J Sports*
379 *Med* **49**, 1213–1218.
- 380 Okano AH, Fontes EB, Montenegro RA, Farinatti P de TV, Cyrino ES, Li LM, Bikson M &
381 Noakes TD (2015b). Brain stimulation modulates the autonomic nervous system,
382 rating of perceived exertion and performance during maximal exercise. *Br J Sports*
383 *Med* **49**, 1213–1218.
- 384 Oki K, Mahato NK, Nakazawa M, Amano S, France CR, Russ DW & Clark BC (2016).
385 Preliminary Evidence That Excitatory Transcranial Direct Current Stimulation
386 Extends Time to Task Failure of a Sustained, Submaximal Muscular Contraction in
387 Older Adults. *J Gerontol A Biol Sci Med Sci*; DOI: 10.1093/gerona/glw011.
- 388 Oliviero A, Profice P, Tonali PA, Pilato F, Saturno E, Dileone M, Ranieri F & Di Lazzaro V
389 (2006). Effects of aging on motor cortex excitability. *Neurosci Res* **55**, 74–77.
- 390 Palm U, Keeser D, Schiller C, Fintescu Z, Reisinger E, Padberg F & Nitsche M (2008). Skin
391 lesions after treatment with transcranial direct current stimulation (tDCS). *Brain*
392 *Stimul Basic Transl Clin Res Neuromodulation* **1**, 386–387.
- 393 Poreisz C, Boros K, Antal A & Paulus W (2007). Safety aspects of transcranial direct current
394 stimulation concerning healthy subjects and patients. *Brain Res Bull* **72**, 208–214.
- 395 Reardon S (2016). “Brain doping” may improve athletes’ performance. *Nature* **531**, 283–284.
- 396 Sidhu SK, Cresswell AG & Carroll TJ (2013). Corticospinal responses to sustained
397 locomotor exercises: moving beyond single-joint studies of central fatigue. *Sports*
398 *Med Auckl NZ* **43**, 437–449.

- 399 Takarada Y, Mima T, Abe M, Nakatsuka M & Taira M (2014). Inhibition of the primary
400 motor cortex can alter one's "sense of effort": effects of low-frequency rTMS.
401 *Neurosci Res* **89**, 54–60.
- 402 Taylor JL, Butler JE, Allen GM & Gandevia SC (1996). Changes in motor cortical
403 excitability during human muscle fatigue. *J Physiol* **490 (Pt 2)**, 519–528.
- 404 Vitor-Costa M, Okuno NM, Bortolotti H, Bertollo M, Boggio PS, Fregni F & Altimari LR
405 (2015). Improving Cycling Performance: Transcranial Direct Current Stimulation
406 Increases Time to Exhaustion in Cycling. *PloS One* **10**, e0144916.
- 407 Williams PS, Hoffman RL & Clark BC (2013a). Preliminary evidence that anodal
408 transcranial direct current stimulation enhances time to task failure of a sustained
409 submaximal contraction. *PloS One* **8**, e81418.
- 410 Williams PS, Hoffman RL & Clark BC (2013b). Preliminary Evidence That Anodal
411 Transcranial Direct Current Stimulation Enhances Time to Task Failure of a
412 Sustained Submaximal Contraction ed. Hug F. *PLoS ONE* **8**, e81418.
- 413 Zénon A, Sidibé M & Olivier E (2015). Disrupting the supplementary motor area makes
414 physical effort appear less effortful. *J Neurosci Off J Soc Neurosci* **35**, 8737–8744.

415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432

Provisional

433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463

Provisional

Table 1. List of tDCS studies on exercise performance.

Articles	Sample size	Placement of electrodes	Stimulation duration	Stimulation Intensity	Electrode size	Control condition	Muscle group investigated	Exercise protocol	Performance result
Cogiamanian et al., (2007)	Study 1, n= 9; Study 2, n= 15	Anodal right M1, cathodal right shoulder	10 min	1.5 mA	35 cm ²	Cathodal and control	Left elbow flexors	Isometric TTF at 35% MVC	Improvement
Muthalib et al., (2013)	n=15	Anodal right M1, cathodal right shoulder	10 min	2 mA	24 cm ²	Sham	Left elbow flexors at 90° flexion	Isometric TTF at 30% MVC	No improvement
Kan et al., (2013)	n=15	Anodal right M1, cathodal contralateral shoulder	10 min	2 mA	24 cm ²	Sham	Elbow flexors at 90° flexion	Isometric TTF at 30% MVC	No improvement
Williams et al., (2013)	n=18	Anodal right M1, cathodal left forehead	20 min during TTF	1.5 mA	35 cm ²	Sham	Left elbow flexors	Isometric TTF at 20% MVC	Improvement
Okano et al., (2013)	n=10	Anodal T3, cathodal over Fp2	20 min	2 mA	35 cm ²	Sham	Lower limbs	Cycling, from 15W + 25 Wmin-1	Improvement of ~4%
Angius et al., (2015)	n=9	Anodal right M1, cathodal Fp2	10 min	2 mA	35 cm ²	Sham & control	Lower limbs	Cycling, at 70 % of peak power	No improvement
Costa et al., (2015)	n= 11	Active over Cz and reference over occipital protuberance	13 min	2.0 mA	35 cm ²	Sham & cathodal	Lower limbs	Cycling, at 80 % peak power	Improvement
Abdelmoula et al., (2016)	n= 11	Anodal left M1, cathodal right shoulder	10 min	1.5 mA	35 cm ²	Sham	Elbow flexors	Isometric TTF at 35% MVC	Improvement
Oki et al., (2016)	n=13	Anode over right M1, cathode over the left forehead	Max 20 min during TTF	1.5 mA	35 cm ²	Sham	Elbow flexors	Isometric TTF at 20 % MVC	Improvement
Angius et al., (2016)	n=12	Bilateral montage, active electrode over M1 and reference over the ipsilateral shoulder	10min	2.0 mA	35 cm ²	Sham & cathodal	Lower limbs	Cycling, at 70 % of peak power	Improvement
Barwood et al., (2016)	study 1, n= 6; study 2, n= 8	Anodal over T3, cathodal over the contralateral Fp2	20 min	Study 1= 1.5 mA Study 2= 2.0 mA	35 cm ²	Sham	Lower limbs	Study 1: cycling TT 20 km cycling; Study 2: cycling 25 min at 55% of peak power + TTF at 75% of peak power	No improvement
Angius et al., (2016)	n= 9	Extracephalic: anodal left M1 and cathodal over ipsilateral shoulder; Cephalic: anodal left M1 and cathodal over dorsolateral right prefrontal cortex	10 min	2.0 mA	35 cm ²	Sham & control	Right knee extensors	Isometric TTF at 20% MVC	Improvement with extracephalic montage

Primary motor cortex (M1); maximal voluntary contraction (MVC); time trial (TT); time to task failure (TTF);